Final Report on NASA Grant NAG 2-485
"Data Analysis for the Pioneer Venus Electric Field Detector"

Dec 28, 1995

This grant supported data analysis of the Pioneer Venus Orbiter Electric Field Detector (OEFD) from 10/1/87 to 9/30/95. The late Frederick L. Scarf was the original Principal Investigator on this grant. Unfortunately, he passed away in July 1988. After this Robert J. Strangeway was named as PI on the grant. In this final report we will briefly describe some of the research highlights. Much of the report will concentrate on the later results.

In terms of scientific output, the appendix shows that over 44 papers have been published with the support of this grant. There have been 9 invited papers and 58 contributed papers presented at scientific meetings. In addition two graduate students, Chang-Ming Ho, and Gregory K. Crawford carried out their thesis work with the support of this grant.

The Pioneer Venus OEFD measures plasma wave electric fields at four frequencies 100 Hz, 730 Hz, 5.4 kHz, and 30 kHz [Scarf et al., 1980]*. Although limited in frequency resolution, this allows us to study various plasma wave phenomena, including whistler-mode waves (≈ 100 Hz), ion acoustic waves (≈ 730 Hz and 5.4 kHz), and electron plasma oscillations (≈ 30 kHz).

Of the many topics investigated with the OEFD, the following stand out: 1) The plasma wave evidence for lightning on Venus; 2) Plasma waves observed upstream of the Venus bow shock; and 3) Plasma waves near the dayside ionopause of Venus.

1) The plasma wave evidence for lightning on Venus

The Pioneer Venus OEFD data are often cited as evidence for lightning on Venus. This topic has been a fruitful research topic throughout the lifetime of the grant. The evidence for lightning is now very strong. Much of this evidence is presented in the papers given below [papers 1, 2, 5, 11, 12, 14, 15, 16, 17, 22, 23, 29, 33, 34, 35, 40, 41]. It is now clear that many of the electric field bursts detected by the Pioneer Venus Orbiter are consistent with radiation propagating through the ionosphere from below. The only likely atmospheric source is planetary lightning. However, any electromagnetic waves generated by lightning will tend to be absorbed by the ionosphere. Only a small fraction of the wave energy could escape to be detected by a spacecraft such as Pioneer Venus. In terms of ionospheric and plasma wave phenomena, a clear demonstration that the waves can escape will probably clinch the debate. We have begun an analysis of the transmission characteristics of the ionosphere [paper 44], but a more thorough understanding requires further support. Having demonstrated that the plasma waves appear to be due to lightning, we are then left with the unresolved question, which is beyond the scope of the present grant. How does a planet like Venus generate lightning?

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* Scarf, F. L., W. W. L. Taylor, and P. F. Virobik, The Pioneer Venus Orbiter plasma wave investigation, *IEEE Trans. Geosci. Remote Sens., GE-18*, 36–38, 1980.

Chang-Ming Ho's Ph. D. Thesis was concerned with the plasma wave evidence for lightning on Venus.

2) Plasma waves observed upstream of the Venus bow shock

One of the major successes of the Pioneer Venus OEFD was the generation of plasma wave maps of the region upstream of the Venus bow shock, known as the foreshock. The Pioneer Venus OEFD data provided an extensive set of data, not available at any other planet. For example, we found that waves generated by electrons streaming away form the shock only extend a finite distance upstream. Presumably the free energy supplied by the back-streaming electrons is removed by the waves. However, comparison wth terrestrial observations show that the waves at the earth extend much further (in absolute scale), and it appears the amount of free energy available is closely related to the shock size. Results of these studies were presented in papers [3, 5, 9, 20, 28, 37, 39].

Much of Gregory K. Crawford's Ph. D. Thesis was devoted to mapping the plasma waves within the Venus foreshock.

3) Plasma waves near the dayside ionopause of Venus

The last topic we shall describe here concerns the plasma waves observed above the dayside ionopause of Venus. Although originally cited as a source of energy for the topside ionosphere, much of our more recent work shows that the waves are probably more involved in the coupling of planetary ions to the solar wind [see papers 5, 19, 21]. As such, the waves may be part of the process whereby planetary ions are "picked-up" by the solar wind, and hence lost from the near-Venus environment. This is one mechanism for scavenging the atmosphere, since the planetary ions ultimately come from ionized planetary neutrals within the atmosphere. In addition, similar wave modes appear to occur above the ionopause of Mars. Thus the Pioneer Venus OEFD data provide an important clue for understanding solar-wind ionosphere coupling at the unmagnetized planets.

Concluding Remarks

The Pioneer Venus OEFD data have been submitted to the Planetary Data System (PDS), and the National Space Science Data Center (NSSDC). The former provides a means for continued distribution of the data, a full set of the OEFD data from all 5055 orbits of PVO are available from the PDS. The NSSDC submission provides the "deep archive", ensuring that the data are not lost.

Many of the results presented here are accessible via the internet. Principal Investigator Robert J. Strangeway maintains a set of world-wide-web documents that give examples of some of the research carried out with this grant, as well as poster papers, and preprints of papers. The URL for his page is "http://www-ssc.igpp.ucla.edu/~strange". We intend to maintain these pages into the indefinite future.

Publications and Presentations Supported by NASA Grant NAG 2-485

This section gives a partial list of the papers and presentations supported by NASA Grant NAG 2-485. The list does not include papers which used Pioneer Venus OEFD data, but did not have Principal Investigator Strangeway as a co-author. Nor does it include papers written by the original Principal Investigator (Frederick L. Scarf), who passed away in 1988.

Theses Supported by NASA Grant NAG 2-485:

1. Ho, C.-M., "Plasma Waves in the Nightside Ionosphere of Venus", 1993.

2. Crawford, G. K., "A Study of Plasma Waves Arising from the Solar Wind Interaction with Venus", 1993.

Publications Supported by NASA Grant NAG 2-485:

1. Russell, C. T., M. von Dornum, and R. J. Strangeway, VLF bursts in the night ionosphere of Venus: estimates of the Poynting flux, *Geophys. Res. Lett.*, *16*, 579, 1989.

2. Strangeway, R. J., Radioemission source disputed, *Nature*, *345*, 213, 1990.

3. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Electron plasma oscillations in the Venus foreshock, *Geophys. Res. Lett.*, *17*, 1805, 1990.

4. Intriligator, D. S., L. H. Brace, S. H. Brecht, W. C. Knudsen, F. L. Scarf, R. J. Strangeway, and H. A. Taylor, Jr., Evidence for unusually high densities of plasma in the Venusian ionosheath, *Geophys. Res. Lett.*, *18*, 61, 1991.

5. Strangeway, R. J., Plasma Waves at Venus, *Space Sci. Rev.*, *55*, 275, 1991.

6. Perez-de-Tejada, H., D. S. Intriligator, and R. J. Strangeway, Steady-state transition in the Venus ionosheath, *Geophys. Res. Lett.*, *18*, 131, 1991.

7. Ong, M., J. G. Luhmann, C. T. Russell, R. J. Strangeway, and L. H. Brace, Venus ionospheric "clouds": relationship to the magnetosheath field geometry, *J. Geophys. Res.*, *96*, 11133, 1991.

8. Moses, S. L., C. F. Kennel, R. J. Strangeway, R. Grard, and C. Nairn, Characteristics of spectra from the Martian bow shock and comparison with Venus, Earth, AMPTE, Jupiter, and Saturn, *J. Geophys. Res.*, *96*, 11221, 1991.

9. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Variations in plasma wave intensity with distance along the electron foreshock boundary at Venus, *Adv. Space Res.*, *11(9)*, 93, 1991.

10. Ong, M., J. G. Luhmann, C. T. Russell, R. J. Strangeway, and L. H. Brace, Venus ionospheric tail rays: spatial distributions and interplanetary magnetic field control, *J. Geophys. Res.*, *96*, 17751, 1991.

11. Sonwalkar, V. S., D. L. Carpenter, and R. J. Strangeway, Testing radio bursts observed on the nightside of Venus for evidence of whistler mode propagation from lightning, *J. Geophys. Res.*, *96*, 17763, 1991.

12. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Occurrence characteristics of VLF bursts in the nightside ionosphere of Venus, *J. Geophys. Res.*, *96*, 21361, 1991.

13. Kivelson, M. G., C. F. Kennel, R. L. McPherron, C. T. Russell, D. J. Southwood, R. J. Walker, C. M. Hammond, K. K. Khurana, R. J. Strangeway, and P. J. Coleman, Magnetic field studies of the solar wind interaction with Venus from the Galileo flyby, *Science*, *253*, 1518, 1991.

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15. Russell, C. T., and R. J. Strangeway, Venus lightning: an update, *Adv. Space Res.*, *12(9)*, 43, 1992.

16. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Control of VLF burst activity in the nightside ionosphere of Venus by the magnetic field orientation, *J. Geophys. Res.*, *97*, 11,673, 1992.

17. Strangeway, R. J., An assessment of lightning or in situ instabilities as a source for whistler-mode waves in the night ionosphere of Venus, *J. Geophys. Res.*, *97*, 12,203, 1992.

18. Perez-de-Tejada, H., D. S. Intriligator, and R. J. Strangeway, Magnetic field properties of the intermediate transition of the Venus ionosheath, *Geophys. Res. Lett.*, *20*, 991, 1993.

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22. Strangeway, R. J., C. T. Russell, and C. M. Ho, Observation of intense wave bursts at very low altitudes within the Venus nightside ionosphere, *Geophys. Res. Lett.*, *20*, 2771–2774, 1993.

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25. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Evidence for Langmuir oscillations and a low density cavity in the Venus magnetotail, *Geophys. Res. Lett., 20,* 2775–2778, 1993.

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28. Crawford, G. K., R. J. Strangeway, and C. T. Russell, VLF imaging of the Venus foreshock, *Geophys. Res. Lett., 20,* 2801–2804, 1993.

29. Ho, C.-M., R. J. Strangeway, and C. T. Russell, The mystery of VLF bursts in the nightside Venus ionosphere: Local instabilities or atmospheric discharge, in *Physics of Space Plasmas (1992),* SPI Conference Proceedings and Reprint Series, Number 12, p. 529, 1993.

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33. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Spatial distribution of plasma wave activity in the nightside ionosphere of Venus, *Planet. Space Sci., 42,* 813–823, 1994.

34. Strangeway, R. J., An assessment of plasma instabilities or planetary lightning as a source for the VLF bursts detected at Venus, *Adv. Space Res., 15,* 4(89)–4(92), 1995.

35. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Venus planetary lightning rate as deduced from VLF bursts, *Adv. Space Res., 15,* (4)93–4(98), 1995.

36. Perez-de-Tejada, H., D. S. Intriligator, and R. J. Strangeway, Plasma expansion layer in the Venus inner ionosheath, *Adv. Space Res., 15,* (4)131–4(140), 1995.

37. Strangeway, R. J., and G. K. Crawford, VLF waves in the foreshock, *Adv. Space Res., 15,* (8/9)29–(8/9)42, 1995.

38. Greenstadt, E.W., G. Le, and R. J. Strangeway, ULF waves in the foreshock, *Adv. Space Res., 15,* (8/9)71–(8/9)84, 1995.

39. Strangeway, R. J., and G. K. Crawford, Comparison of upstream phenomena at Venus and Earth, *Adv. Space Res., 16,* (4)125–(4)136, 1995.

40. Strangeway, R. J., The plasma wave evidence for lightning on Venus, *J. Atmos. Terr. Phys., 57,* 537–556, 1995.

41. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Venus nightside irregularities and their relationship to VLF bursts, *J. Geophys. Res., 100,* 9697–9705, 1995.

42. Perez-de-Tejada, H., D. S. Intriligator, and R. J. Strangeway, Intermediate transition in the Venus ionosheath, *J. Geophys. Res., 100,* 14,523–14,535, 1995.

43. Mihalov, J. D., and R. J. Strangeway, Large solar wind disturbances during late May and early June 1991, *Solar Physics, 160,* 363–370, 1995.

44. Strangeway, R. J., Collisional Joule dissipation in the ionosphere of Venus: The importance of electron heat conduction, in press, *J. Geophys. Res.*, 1995.

Invited Talks Supported by NASA Grant NAG 2-485:

1. Strangeway, R. J., Plasma waves at Venus: Pioneer Venus observations, AGU Spring Meeting, Baltimore, *EOS, Trans. AGU, 70,* 425, 1989.

2. Strangeway, R. J., and C. T. Russell, Pioneer Venus VLF measurements: Implications for lightning, AGU Spring Meeting, Baltimore, *EOS, Trans. AGU, 72,* 172, 1991.

3. Strangeway, R. J., Expected VLF wave observations during the Pioneer Venus final encounter, *EOS, Trans. AGU, 73(14),* 192, American Geophysical Union Spring Meeting, Montreal, 1992.

4. Strangeway, R. J., Evidence for lightning on Venus, *LPI Contribution No. 789, 122,* International Colloquium on Venus, Pasadena, 1992.

5. Russell, C. T., and R. J. Strangeway, Low altitude magnetic fields and plasma waves, *Eos, Trans. AGU, 74(16),* 186, American Geophysical Union Spring Meeting, Baltimore, 1993.

6. Strangeway, R. J., The plasma wave evidence for lightning on Venus, XXIVth General Assembly of the International Union of Radio Science, Kyoto, Japan, 1993.

7. Strangeway, R. J., Comparison of upstream phenomena at Venus and Mars, 30th COSPAR Scientific Assembly, p143 (abstract), Hamburg, Germany, 1994.

8. Strangeway, R. J., VLF waves in the foreshock, 30th COSPAR Scientific Assembly, p167 (abstract), Hamburg, Germany, 1994.

9. Greenstadt, E.W., G. Le, and R. J. Strangeway, ULF waves in the foreshock, 30th COSPAR Scientific Assembly, p168 (abstract), Hamburg, Germany, 1994.

Contributed Papers Supported by NASA Grant NAG 2-485:

1. Ho, C.-M., M. von Dornum, R. J. Strangeway, and C. T. Russell, "Polarization of low frequency waves observed in the nightside Venus ionosphere", *EOS, Trans. AGU, 69*, 1294, American Geophysical Union Fall Meeting, San Francisco, 1988.

2. von Dornum, M., C. T. Russell, and R. J. Strangeway "Altitude dependence of the amplitude of impulsive VLF noise in the nightside Venus ionosphere", *EOS, Trans. AGU, 69*, 1294, American Geophysical Union Fall Meeting, San Francisco, 1988.

3. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Electron plasma oscillations in the Venus foreshock, *EOS, Trans. AGU, 70*, 1171, American Geophysical Union Fall Meeting, San Francisco, 1989.

4. Ho, C.-M., C. T. Russell, and R. J. Strangeway, VLF bursts in the night ionosphere of Venus: possible association with density gradients, *EOS, Trans. AGU, 70*, 1178, American Geophysical Union Fall Meeting, San Francisco, 1989.

5. Strangeway, R. J., C.-M. Ho, and C. T. Russell, VLF spherics in the night ionosphere of Venus: estimate of the flash rate, *EOS, Trans. AGU, 70*, 1178, American Geophysical Union Fall Meeting, San Francisco, 1989.

6. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Plasma waves observed in the Venus electron and ion foreshock regions, *EOS, Trans. AGU, 71*, 550, American Geophysical Union Spring Meeting, Baltimore, 1990.

7. Mahajan, K. K., J. M. Grebowsky, R. E. Hartle, L. H. Brace, W. T. Kasprzak, and R. J. Strangeway, Some features of plasma waves at the Venus ionopause, *EOS, Trans. AGU, 71*, 550, American Geophysical Union Spring Meeting, Baltimore, 1990.

8. Ho, C.-M., C. T. Russell, and R. J. Strangeway, Statistical studies of the occurrence of VLF bursts in the night ionosphere of Venus, *EOS, Trans. AGU, 71*, 550, American Geophysical Union Spring Meeting, Baltimore, 1990.

9. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Electron plasma oscillations in the Venus foreshock, XXVIII COSPAR Plenary Meeting (abstract), p36, 1990.

10. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Occurrence characteristics of VLF bursts in the nightside ionosphere of Venus, XXVIII COSPAR Plenary Meeting (abstract), p36, 1990.

11. Russell, C. T., and R. J. Strangeway, Venus lightning: latest results, XXVIII COSPAR Plenary Meeting (abstract), p131, 1990.

12. Strangeway, R. J., C.-M. Ho, and C. T. Russell, Statistical properties of impulsive signals in the nightside ionosphere of Venus, *EOS, Trans. AGU, 71*, 934, Western Pacific Geophysics Meeting, Kanazawa, Japan, 1990.

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16. Crawford, G. K., R. J. Strangeway, C. T. Russell, and J. D. Mihalov, Investigation of plasma wave observations in the ion foreshock of Venus, *EOS, Trans. AGU, 71*, 1515, American Geophysical Union Fall Meeting, San Francisco, 1990.

17. Ho, C.-M., R. J. Strangeway, and C. T. Russell, Control of VLF activity in the nightside ionosphere of Venus by the magnetic field orientation, *EOS, Trans. AGU, 72(17)*, 172, American Geophysical Union Spring Meeting, Baltimore, 1991.

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33. Mihalov, J. D., A. Barnes, and R. J. Strangeway, Solar wind observations at Venus during high solar activity of May –June, 1991, *EOS, Trans. AGU, 73(14)*, 237, American Geophysical Union Spring Meeting, Montreal, 1992.

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41. Strangeway, R. J., and G. K. Crawford, Why plasma waves observed in the Venus plasma mantle are not lower hybrid waves driven by planetary O^+ ions, *EOS, Trans. AGU, 73(43)*, 334, American Geophysical Union Fall Meeting, San Francisco, 1992.

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44. Crawford, G. K., R. J. Strangeway, and C. T. Russell, Asymmetry in Venus VLF electron foreshock emissions, *EOS, Trans. AGU, 73(43)*, 441, American Geophysical Union Fall Meeting, San Francisco, 1992.

45. R. J. Strangeway, C. M. Ho, and C. T. Russell, Plasma wave bursts in the low altitude Venus nightside ionosphere, *Eos, Trans. AGU, 74(16)*, 186, American Geophysical Union Spring Meeting, Baltimore, 1993.

46. C. M. Ho, R. J. Strangeway, C. T. Russell, J. G. Luhmann, and L. H. Brace, IMF control of the nightside ionosphere of Venus, *Eos, Trans. AGU, 74(16)*, 186, American Geophysical Union Spring Meeting, Baltimore, 1993.

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48. R. J. Strangeway, C. T. Russell, and C. M. Ho, Detection of lightning generated ELF waves at very low altitude in the Venus nightside ionosphere, 25th Annual Meeting of the Division for Planetary Sciences, Boulder, 1993.

49. G. K. Crawford, R. J. Strangeway, and C. T. Russell, Plasma waves observed above the dayside ionopause of Venus: evidence for an additional transition layer, *Eos, Trans. AGU, 74(43)*, 375, American Geophysical Union Fall Meeting, San Francisco, 1993.

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52. E. W. Greenstadt, S. L. Moses, F. V. Coroniti, G. K. Crawford, and R. J. Strangeway, Electron plasma oscillations in the foreshock: comparison of occurrence at PVO and ISEE 3, *Eos, Trans. AGU, 74(43)*, 493, American Geophysical Union Fall Meeting, San Francisco, 1993.

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